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Prediction of Vortex-Induced Loads on Wind Tunnel Turning Vanes

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Prediction of Vortex-Induced Loads on Wind Tunnel Turning Vanes

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SYMBOLS

A_i	fraction of vortex core which passes through vane bay i
B	diffuser velocity ratio
C_L	wing lift coefficient, $\frac{L}{qS}$
c	wing or vane chord
c_l	section lift coefficient, $\frac{l}{qc}$
d	section drag
F_i	fraction of vorticity through vane bay i
L	wing lift
l	section lift
q	dynamic pressure, $\frac{1}{2} \rho U^2$
r	radius of vortex core
S	wing reference area
U	wind tunnel free-stream velocity
V_θ	vortex-induced tangential velocity
z	vertical coordinate
α	angle of attack
Γ	circulation of tip vortex
ρ	air density

Subscripts

ts	test section
1	at vane set 1
c	vortex core

SUMMARY

Models tested in the National Full-Scale Aerodynamic Complex at NASA Ames Research Center can generate strong wake vortices which in turn can induce large increases in the local loads on the turning vanes that are located downstream from the two test sections. A three-dimensional panel method which models wake roll up (VSAERO) was used to estimate the magnitude of these loads. In the simulation a rectangular wing at angle of attack sheds a wake which is allowed to roll up and interact with a smaller chord, high-aspect ratio wing which represents a single vane. This analysis was found to be in good agreement with experimental data and consistent with previously reported results. A method is presented for the correction of the panel code results for the effects of vane set solidity and of the vortex passage through a diffuser before it interacts with the vane set. This analysis is then used to estimate the induced vortex loads on the vane sets downstream from the 40- by 80-ft and 80- by 120-ft test sections. The results indicate that the induced local loads on a vane can, in some cases, be more than 50% of the steady-state turning loads of an individual vane.

INTRODUCTION

The aerodynamic loads acting on the various components of a low-speed wind tunnel can be greatly influenced by a model in the test section. This is particularly true in a facility such as the National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames Research Center in which large, high-lift, and powered models are routinely tested. Of particular concern is the possibility of large induced loads on the turning vanes downstream of the test section because of the vortex wakes that are generated by high-lift models. The energetic tip vortices associated with these wakes can have a significant influence on the local loads carried by the turning vanes downstream of the model. It is therefore important to estimate the magnitude of the vortex loads on all affected vane sets in order to assure safe operation of the wind tunnel.

A planview of the NFAC is shown in figure 1. The vane sets most strongly affected by the presence of wake vortices are those located immediately downstream of the two test sections. For operation in the 40 by 80 mode, vane set 1 is most affected whereas vane sets 4 and 5 are most affected during the 80 by 120 operation. (The 40- by 80-ft and 80- by 120-ft designations refer to the dimensions of the two test sections in feet.) In order to estimate the maximum induced loads on the vanes, the maximum lift that is generated by a model must be known. For the 40- by 80-ft test section this is limited by the scale system. The scales can accommodate a dead load of 70,000 lb and can operate with an upward load of 30,000 lb giving a maximum lift load of 100,000 lb. The scale system in the 80- by 120-ft test

section is capable of measuring lift loads in excess of 250,000 lb; however, upon investigating the limited operating wind velocity and the types of models which can be mounted in this test section, only about 100,000 lb of lift can be generated (e.g., a Boeing 737 in landing configuration). Thus, a wind-tunnel model lift of 100,000 lb was used in the analysis for both the 40- by 80-ft and the 80- by 120-ft modes of operation.

ANALYSIS METHOD

Panel Code Analysis

The panel code VSAERO (ref. 1) was used as the primary analysis tool for this study. This analysis employs constant-strength doublet panels to model arbitrary three-dimensional surfaces as well as to model lift-generated wakes. Wake roll up is modeled by first computing a potential flow solution with a flat doublet wake. The wake panel edges are then aligned with the local flow direction (i.e., along streamlines). A potential flow solution is then generated for the relaxed wake shape and the process is repeated until a converged wake shape is achieved, usually in 2 or 3 iterations. For the present study the wind-tunnel model was represented by a rectangular wing with an aspect ratio of 5. The rectangular planform was chosen to yield a strong tip vortex. The angle of attack of the wing was adjusted to give 100,000 lb of lift. For vane set 1 the model is in the 40- by 80-ft test section and can have a span of 45 ft. The maximum dynamic pressure in this test section is 274 lb/ft^2 , hence the lift coefficient of the model is 0.91. For the 80 by 120 operation the span can be 90 ft and the test section q is 33.6 lb/ft^2 and the model lift coefficient is 1.8.

A single vane was modeled downstream of the generating wing. The chord of the modeled vane was equal to that of the vane it was to represent. The geometries of the three vanes that were studied and their paneled representations are shown in figure 2. The primary purpose of this analysis is to determine the increment in lift caused by the wake of wind-tunnel models. The camber and angle of attack of the vane in the wind tunnel should not, in a first approximation, affect the increment in lift that is caused by the interaction of the vortex wake with the vane. Therefore, the vanes were modeled using uncambered airfoil sections at zero degrees angle of attack relative to the free stream. Figure 3 is a typical geometry of the generating wing and vane with the resulting rolled-up wake. Cascade effects were neglected in the paneling representation, but they are included later as a correction.

Diffuser Effects

The effect of the diffuser must be accounted for in the calculation of the loads on vane set 1. The initial assumption in the following analysis is that the core area of the wake vortex varies in proportion to the cross-sectional area of the local streamtube. The core radius is defined as the radius of maximum induced tangential

velocity. The relationship between the core radius in the test section (r_{ts}) and the radius at the location of vane set 1 (r_1) is then:

$$\frac{\pi r_1^2}{\pi r_{ts}^2} = B \quad (1)$$

where B is the ratio of the test section velocity to the velocity at vane set 1. For the 40 by 80, B is equal to approximately 1.9 based on measurements made in a 1/50 scale model of the tunnel. It then follows from equation (1) that:

$$r_1 = r_{ts} \sqrt{B} \quad (2)$$

The tangential velocity induced by a vortex is proportional to the inverse of the radius from the vortex center (outside of the core and a maximum at $r = r_c$). Therefore, the maximum tangential velocity induced by the vortex is reduced by the deceleration of the flow in the primary diffuser as:

$$V_{\theta_1} = \frac{V_{\theta_{ts}}}{\sqrt{B}} \quad (3)$$

The induced flow angularity is given by $\alpha = V_{\theta}/U$ so that:

$$\left. \begin{aligned} \alpha_1 &= \frac{V_{\theta_1}}{U_1} \\ \alpha_1 &= \frac{V_{\theta_{ts}}}{\sqrt{B}} \frac{B}{U_{ts}} \\ \alpha_1 &= \sqrt{B} \alpha_{ts} \end{aligned} \right\} \quad (4)$$

The local lift on a wing is given by the equation:

$$l = qc_l c \quad (5)$$

where c_l is the local lift coefficient and c is the local chord. The lift coefficient is proportional to the local angle of attack:

$$c_l = \alpha c_{l_\alpha} \quad (6)$$

Assuming that there is steady, incompressible, uniform flow in the test section and diffuser, conservation of mass requires that the dynamic pressure, q , is inversely proportional to the square of the velocity ratio:

$$q_1 = \frac{q_{ts}}{B^2} \quad (7)$$

Combining equations (4), (5), (6), and (7) yields the ratio of the local load that is induced by the wake on a following vane at the location of vane set 1 to the load that is induced on a follower in the test section. This ratio is given by:

$$\left. \begin{aligned} \frac{l_1}{l_{ts}} &= \frac{q_1 c_{l_1}^c}{q_{ts} c_{l_{ts}}^c} \\ &= \frac{q_1 \alpha_1^c c_{l_\alpha}}{q_{ts} \alpha_{ts}^c c_{l_\alpha}} \\ &= \frac{1}{B^2} \sqrt{B} \\ l_1 &= B^{-1.5} l_{ts} \end{aligned} \right\} \quad (8)$$

Equation (8) is convenient for the present problem since the VSAERO calculation calculates the span loading of the vane as if it were in the test section.

Cascade Effects

In modeling the vane set as a single vane, cascade effects have been ignored. Since vane sets 1 and 5 are fairly dense cascades, the individual vanes in these sets will behave differently than an isolated vane will behave. In particular, the wake vortex of a model will generally be larger than the spacing between adjacent vanes; hence, the effect of the vortex on individual vanes will be less for the cascade case than it will be for an isolated vane. To approximate the effect of multiple vanes, a solution was obtained for a case which includes two vanes, one in which one vane is located between the center of the vortex wake and the second vane. The geometry for this calculation is shown in figure 4. The result of this calculation indicated that the loads on the "shielded" vane were approximately one half as large as they were on the intervening vane. This is attributable to both a shielding effect and to the fact that the second vane was located further from the vortex, thus decreasing the effect of the vortex.

As previously mentioned, the size of the vortex core has an effect on the vane loading. Wake vortex studies (ref. 2) and the wake diffusion model described above indicate that a wake vortex generated in the 40- by 80-ft test section will have a core diameter of approximately 9 ft when it reaches vane set 1. This size core will span 3 bays of the vane set. The effect of spreading the vorticity across the 3 bays was approximated as outlined in figure 5. In this analysis the total vorticity is divided into 3 parts, the strengths of which are given by:

$$r_i = F_i r, \quad \sum_{i=1}^3 F_i = 1 \quad (9)$$

where i refers to the bay number and F_i is equal to the portion of the area of the vortex core passing through bay i divided by the total cross-sectional area of the core. It is assumed that the induced loads on a vane vary linearly with the strength of the vortex. Thus the load induced on a single vane by the vorticity passing through bay i is given by:

$$l_i = \frac{r_i}{r} l = F_i l \quad (10)$$

where l is the load induced by the full wake on a single vane. This result was combined with the effect of the additional vanes which was approximated by a factor $(1/2)^n$ where n is the number of vanes between the vortex segment and the vane of interest. The load on vane j caused by the 3 wake segments is then given by:

$$l_j = l \sum_{i=1}^3 \frac{1}{2}^{n_i} F_i \quad (11)$$

Up to this point the lift loads reported have been for a vane following a vortex-generating wing. The lift is in the direction perpendicular to the free-stream onset flow. In cascade work the lift direction is taken to be along the stagger line of the cascade and drag is perpendicular to the stagger line. The results obtained above must therefore be transformed into this coordinate system as shown in figures 6(a) and 6(b). If the change in vane load that is due to vortex passage as it is calculated above is called Δf , then the changes in lift and drag related to Δf are:

$$\left. \begin{aligned} \Delta l &= \Delta f \sin(\theta) \\ \Delta d &= -\Delta f \cos(\theta) \end{aligned} \right\} \quad (12)$$

It is interesting to note that the drag decreases when Δf is positive. This is because the force vector is rotated forward of the stagger line and thus Δd is negative. This analysis simply addresses the inviscid portion of the drag. Viscous effects will tend to increase the drag. A good (and conservative) estimate of these effects is that the net drag change for $\Delta f > 0$ is the same as for the case of $\Delta f < 0$. In both cases the change in drag is taken to be positive.

RESULTS

The analysis method described above was applied to vane sets 1, 4, and 5. Results are presented first for vane set 1. Figure 7 shows the effect of a vortex wake on the predicted span loading on a single vane. The local lift is normalized by test section dynamic pressure. The z values on the horizontal axis are measured from the floor of the tunnel to the ceiling. The vane model extended beyond these limits in order to eliminate tip effects which would not be present in the wind tunnel. The vortex in the calculation passes the vane at the mid-span of the vane and at approximately 0.2 chord lengths above the surface of the vane. Figure 8 shows the final induced local loads in cascade coordinates after the corrections caused by diffuser and cascade effects are included. Since the stagger angle is 45° , the increments in lift and drag are equal in magnitude.

The final result for vane set 5 is shown in figure 9. In this case the increments in lift and drag are not equal since the stagger angle is 25.6° . The corrections to the VSAERO calculated results that were simpler for this case than they were for vane set 1 in that it was not necessary to take an account of diffuser effects.

Vane set 4 was the simplest vane set to analyze. Since the spacing between vanes is sufficiently large in relation to the size of the vortex, the cascade effects can be neglected. Because there is only a small area change between the test section and the vane set, no correction was applied for this effect. The paneled geometry of vane set 4 matched exactly with the actual vane and so permitted the direct use of the VSAERO results as an estimate of the induced local lift loads. An additional simplification was that the vanes do not carry a turning load since they function merely as a valve in conjunction with vane set 3 in order to configure the facility in either the 80 by 120 or the 40 by 80 mode of operation. The span loading for this vane set is presented in figure 10. The way in which these vanes are supported requires an estimate of the induced pitching moment acting about the pivot point of the vanes. This result is plotted in figure 11.

It should be noted that the loads presented are for one direction of rotation of the tip vortex. There will generally be two vortices shed (one from each wing tip), and they will rotate in opposite directions. Therefore, in using the loads presented in a structural analysis of the vanes, one must look at cases in which the sign of the load is reversed. Also, in actual wind-tunnel tests, the vortex is not constrained to pass down the center of the tunnel as it does in the simulation. Depending on the location, the type of model, and on the magnitude of the vortex meander, the vortex can pass through the vane set well away from the centerline of the wind tunnel. In the process, the precisely antisymmetric loadings presented are altered so that the loadings are offset above or below the center of the vanes. An example of load skewing is shown in figure 12 for the lift loads of vane set 1.

COMPARISON WITH STRIP THEORY AND EXPERIMENT

To gain confidence in the results presented above, some comparisons were made between the panel code, strip theory, and experimental data. One such comparison was made between measured and predicted spanwise lift distributions on a wing following closely behind a larger wing (fig. 13). This test was performed in the NASA 7- by 10-Foot Wind Tunnel at Ames Research Center by McMillan et al. (ref. 3). The lift distribution predicted by VSAERO agrees well with the measured values as shown in figure 14. The calculations were performed for several vortex locations, and the agreement with the experimental data was good for all cases except for those in which the vortex was bifurcated by the following wing. Detailed comparisons of the predictions with this and other experimental data are presented in reference 4.

Strip theory has often been used to estimate the effects of wake vortices on following wings. It is a simple and straightforward method; however, the results are usually not very accurate. Rossow et al. (ref. 2) showed that the induced rolling moment calculated using an uncorrected strip theory is more than double the experimentally measured value whereas a simple vortex lattice calculation gives results within 20% of experimental values.

A strip-theory type calculation was performed for vane set 5 using the induced angles calculated by VSAERO for a model in the 80- by 120-ft test section generating 100,000 lb of lift. These angles were then used in the cascade lift equation from Horlock (ref. 5). This calculation gave a peak local load of 197 lb/ft which is approximately 80% higher than calculated when using VSAERO which was corrected for cascade effects. On the basis of these findings, it appears that the vane loads caused by wake vortices can be adequately predicted using VSAERO and the corrections developed above.

CONCLUDING REMARKS

A method for estimating the turning vane loads that are induced by the wake vortex of a model in either the 40- by 80-ft or 80- by 120-ft test sections of the NFAC has been developed. The basis of the method is the panel code VSAERO. Corrections to the panel code results were presented which account for the effects of the primary diffuser and of the cascade arrangement of the vanes. The method was found to be in good agreement with experimental data and consistent with previously reported results. Estimates of the local load distributions on vane sets 1, 4, and 5 were made based on this analysis method.

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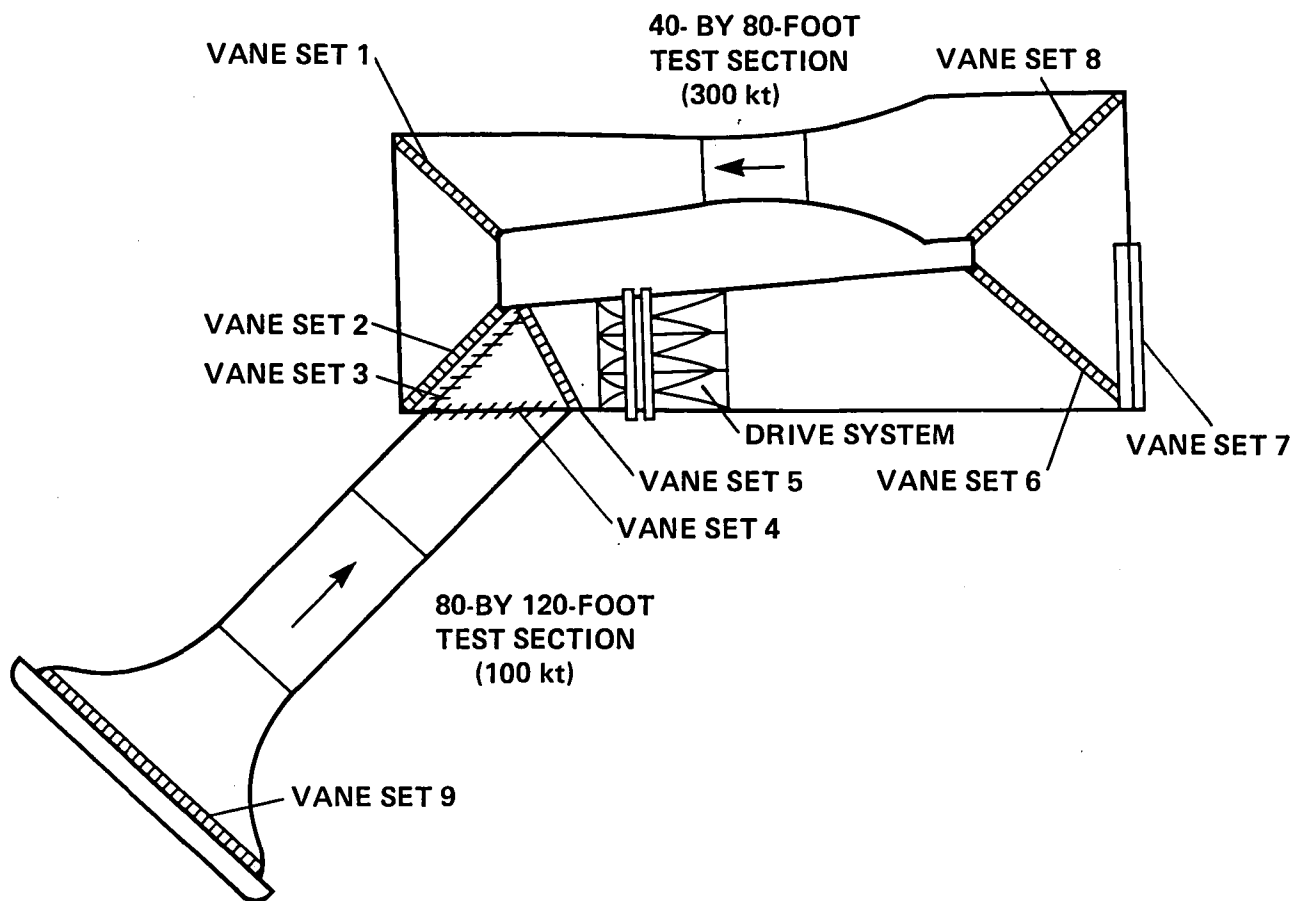


Figure 1.- Plan view of National Full-Scale Aerodynamics Complex (NFAC) showing location of vane sets.

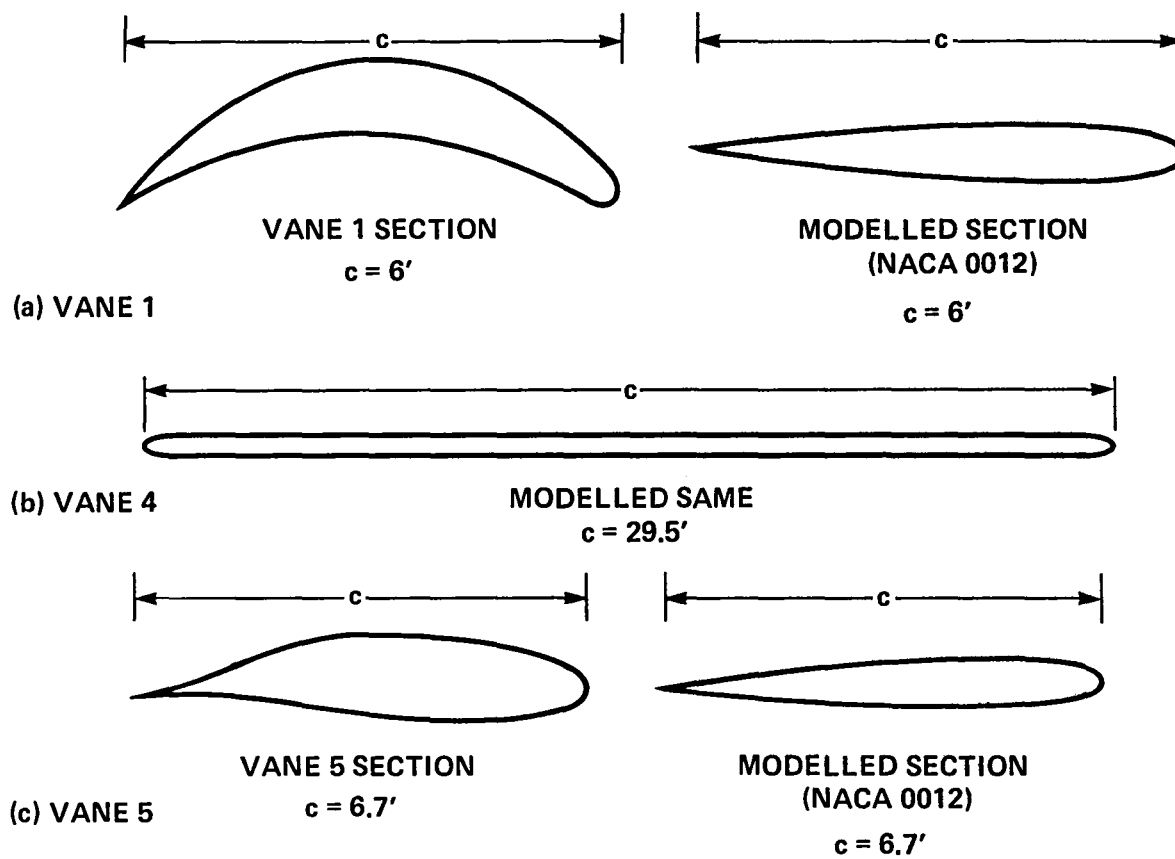
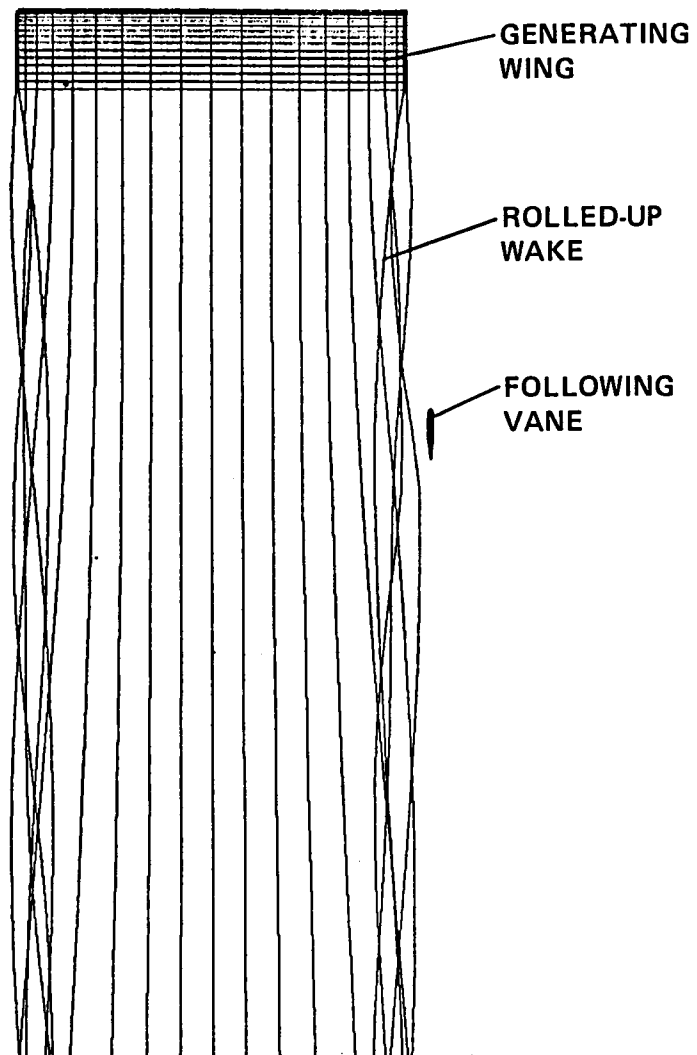
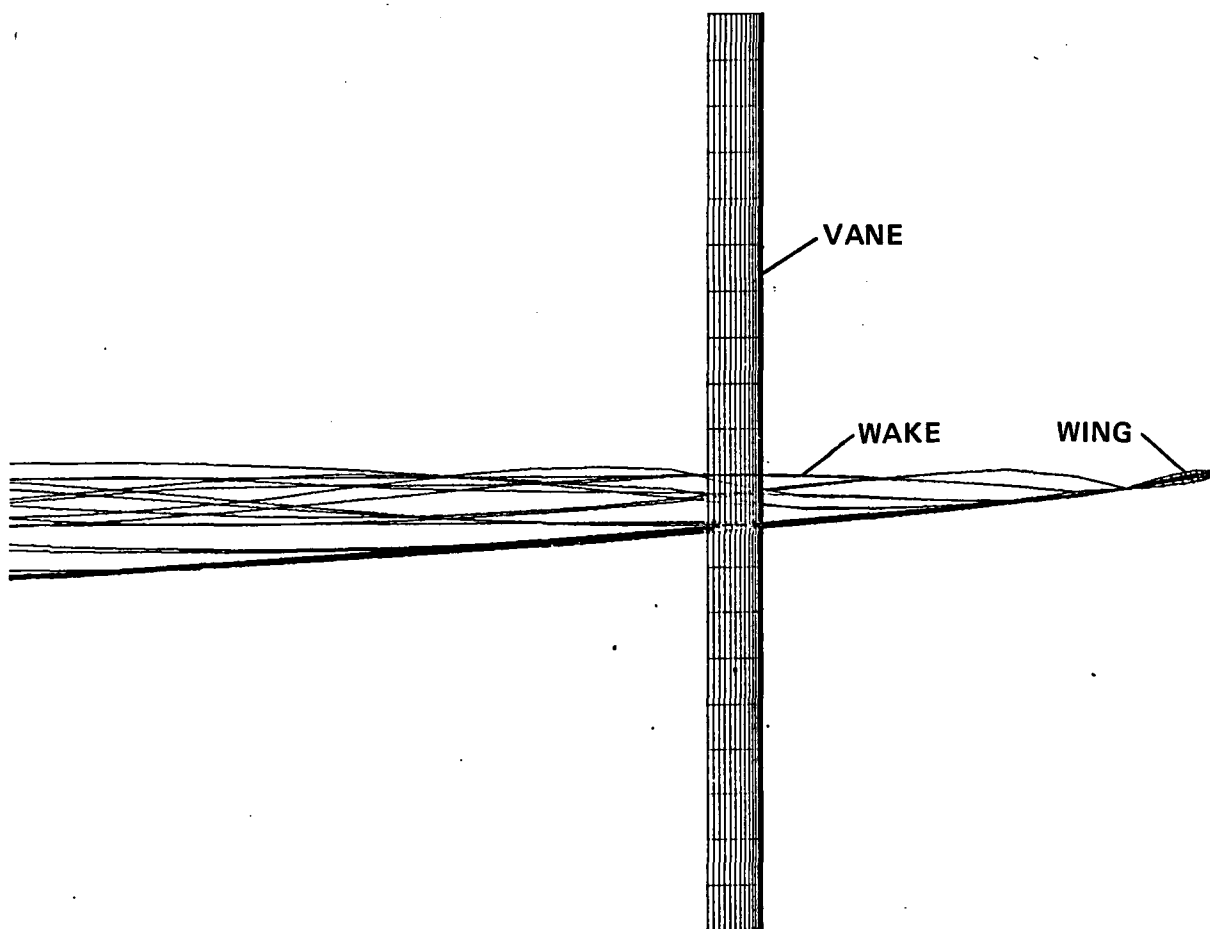


Figure 2.- Airfoil sections of vanes and paneled representations.



(a) Top view.

Figure 3.- Paneled representation.



(b) Side view.

Figure 3.- Concluded.

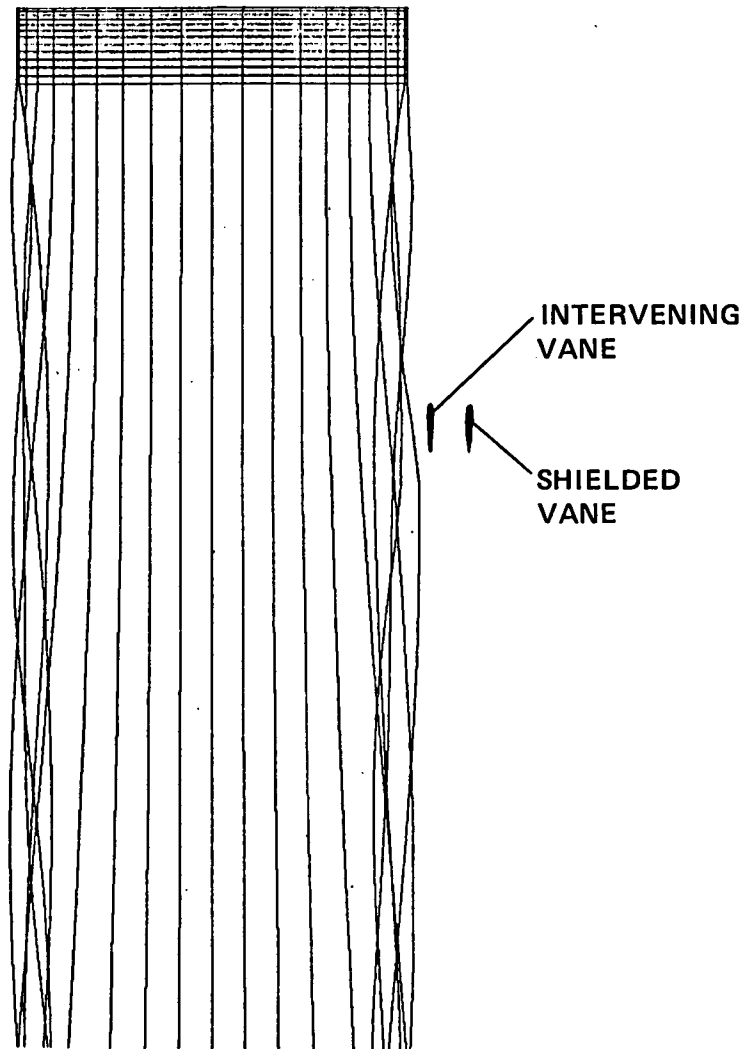


Figure 4.- Simulation of cascade effects.

DIVIDE VORTICITY INTO PARTS:

$$\Gamma_i = \Gamma_o F_i ; F_i = \frac{A_i}{A_o}$$

LET LOAD ON SINGLE VANE DUE TO A SINGLE VORTEX BE Δf . THE INDUCED LOADS ON THE FOUR VANES IN THE SKETCH ARE THEN:

$$\Delta f_{(1)} = [F_1 + (1/2)F_2 + (1/2)^2 F_3] \Delta f$$

$$\Delta f_{(2)} = [F_1 + F_2 + (1/2)F_3] \Delta f$$

$$\Delta f_{(3)} = [(1/2)F_1 + F_2 + F_3] \Delta f$$

$$\Delta f_{(4)} = [(1/2)^2 F_1 + (1/2)F_2 + F_3] \Delta f$$

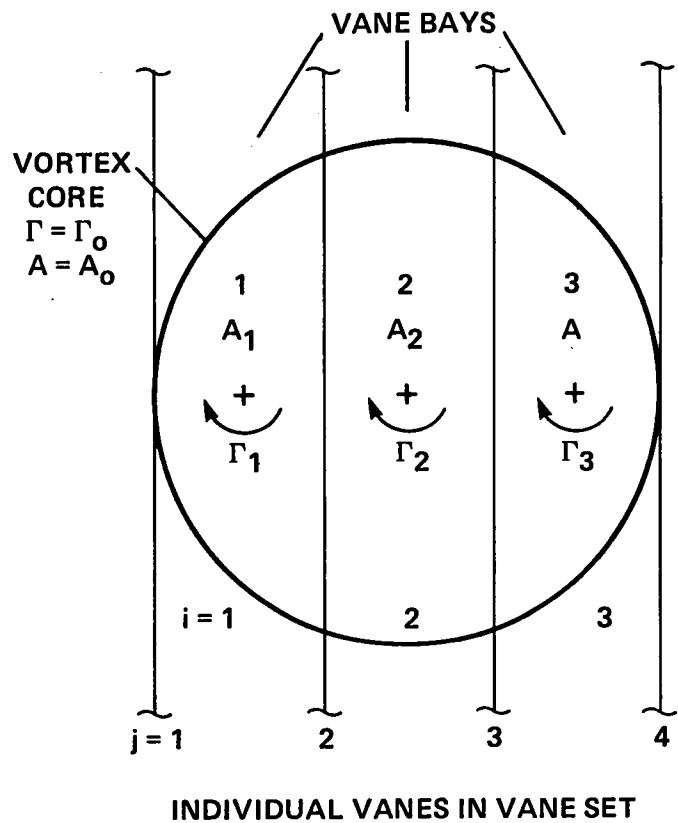
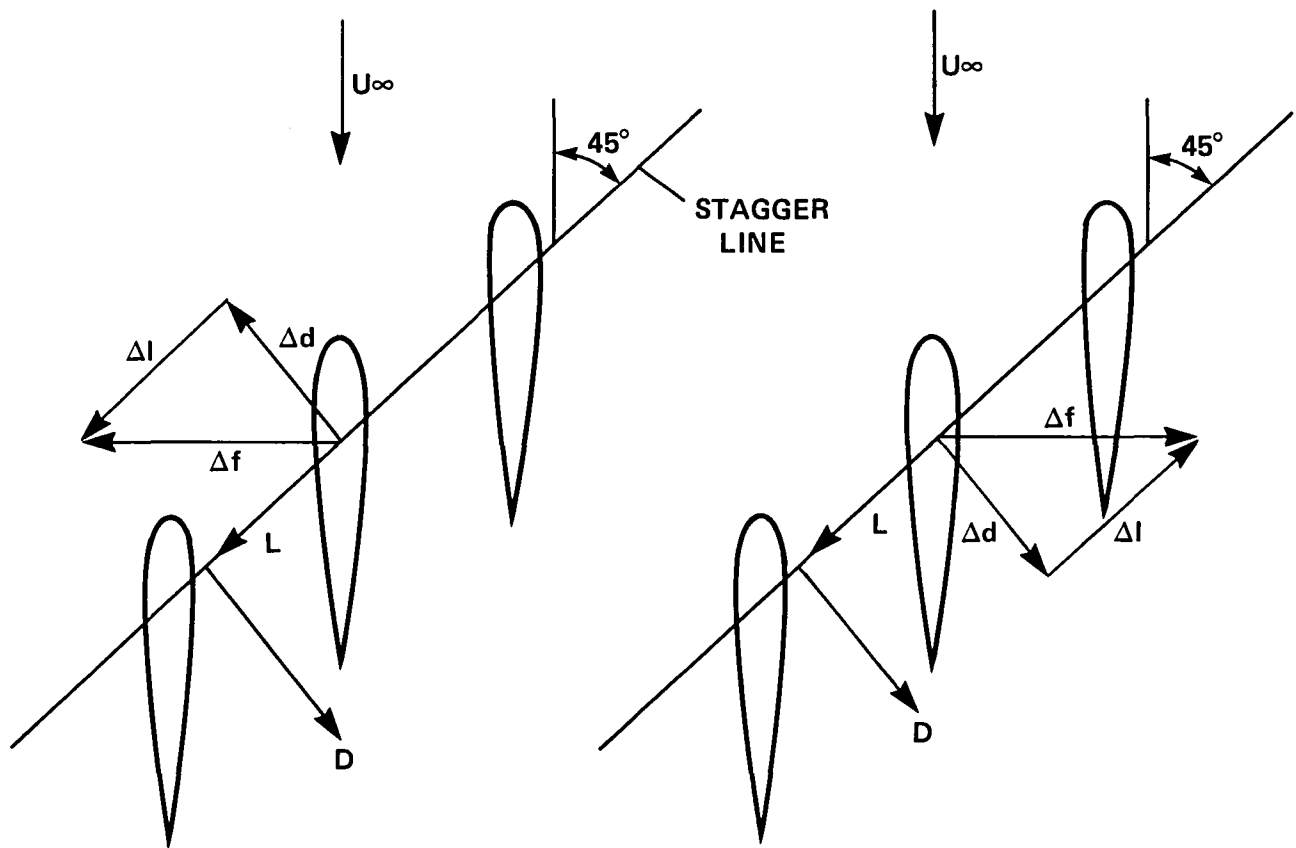


Figure 5.- Analysis to estimate cascade effects.



(a) Caused by positive change in vane load ($\Delta f > 0$).

(b) Caused by negative change in vane load ($\Delta f < 0$).

Figure 6.- Lift and drag increments.

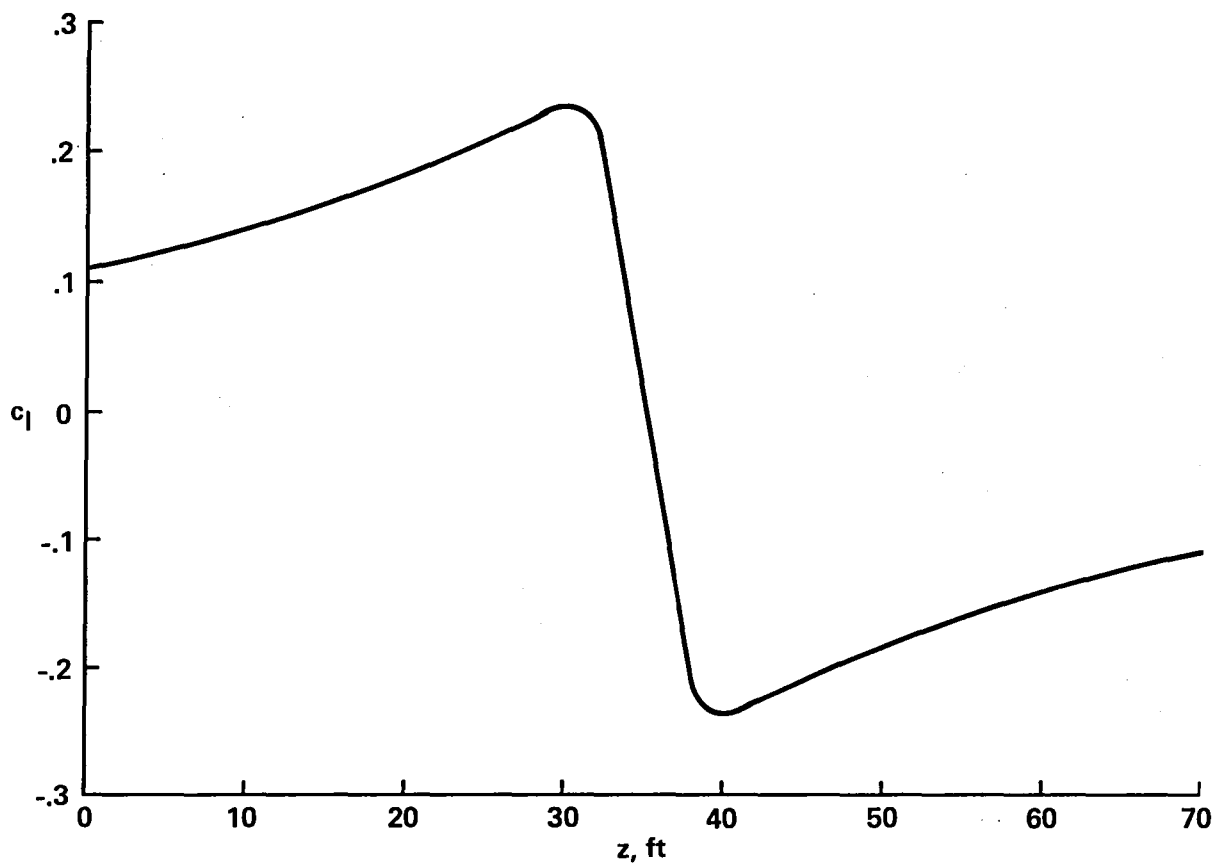


Figure 7.- Vortex-induced load distribution for vane set 1 not corrected for diffuser or cascade effects. Vortex core at $z = 35 \text{ ft}$.

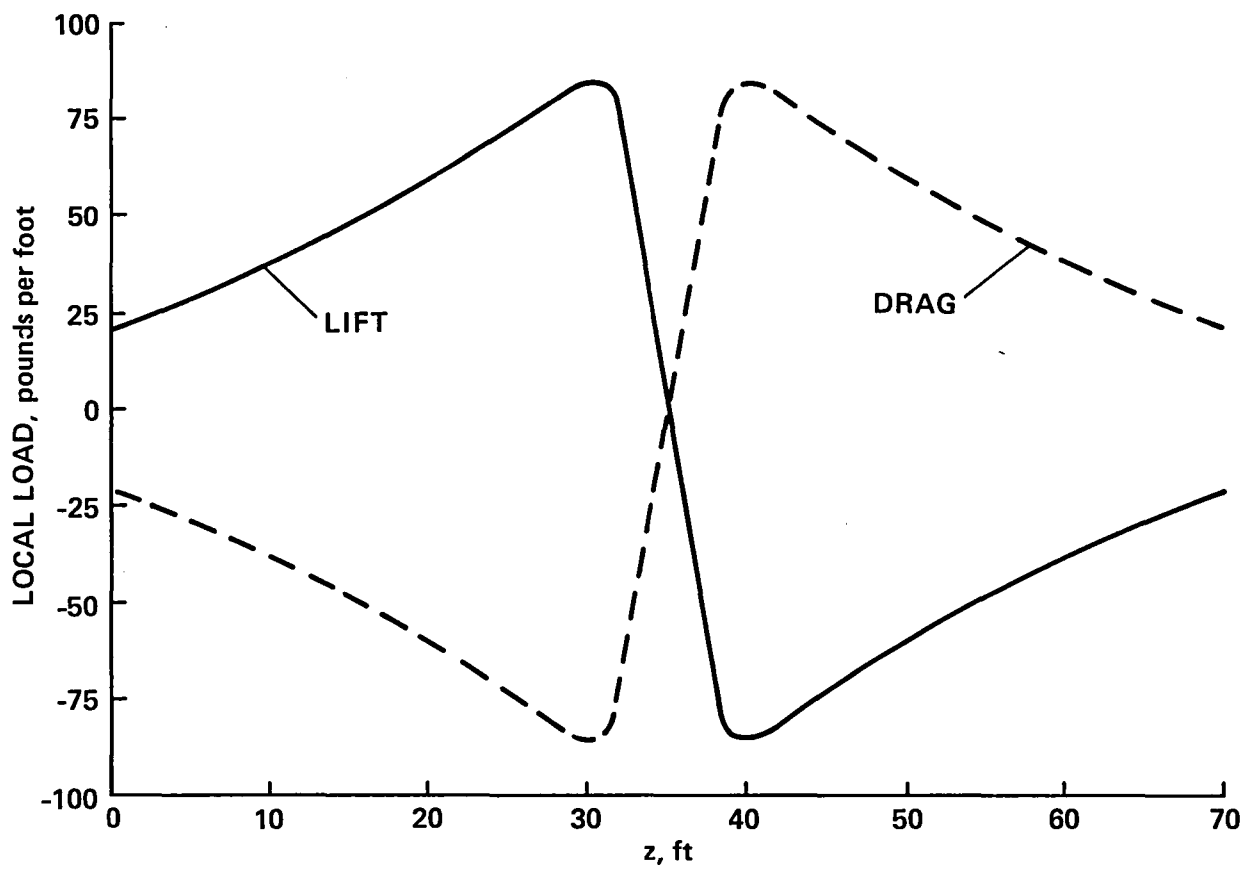


Figure 8.- Predicted vortex-induced load distribution on vane set 1 corrected for diffuser and cascade effects. Vortex core at $z = 35$ ft.

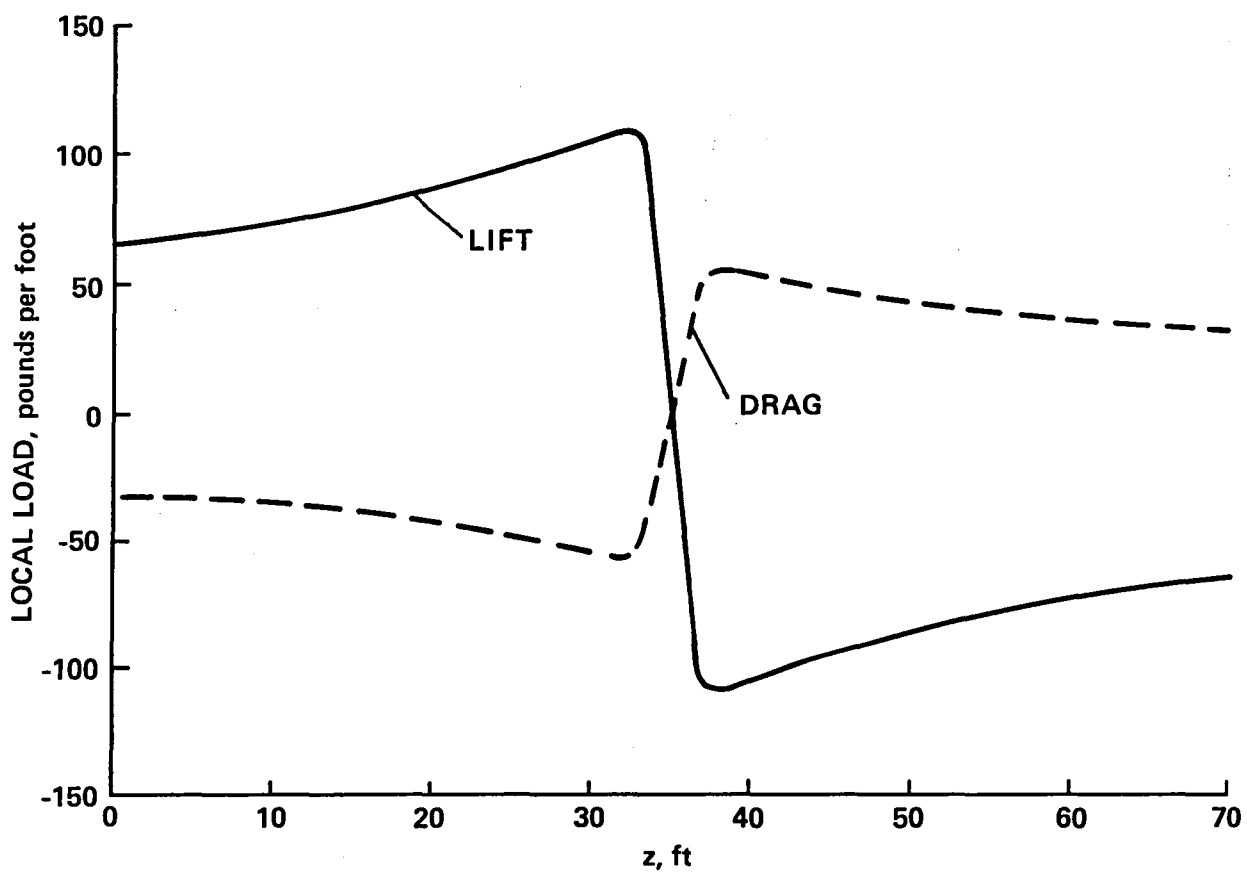


Figure 9.- Predicted vortex-induced load distribution on vane set 5 corrected for cascade effects. Vortex core at $z = 35$ ft.

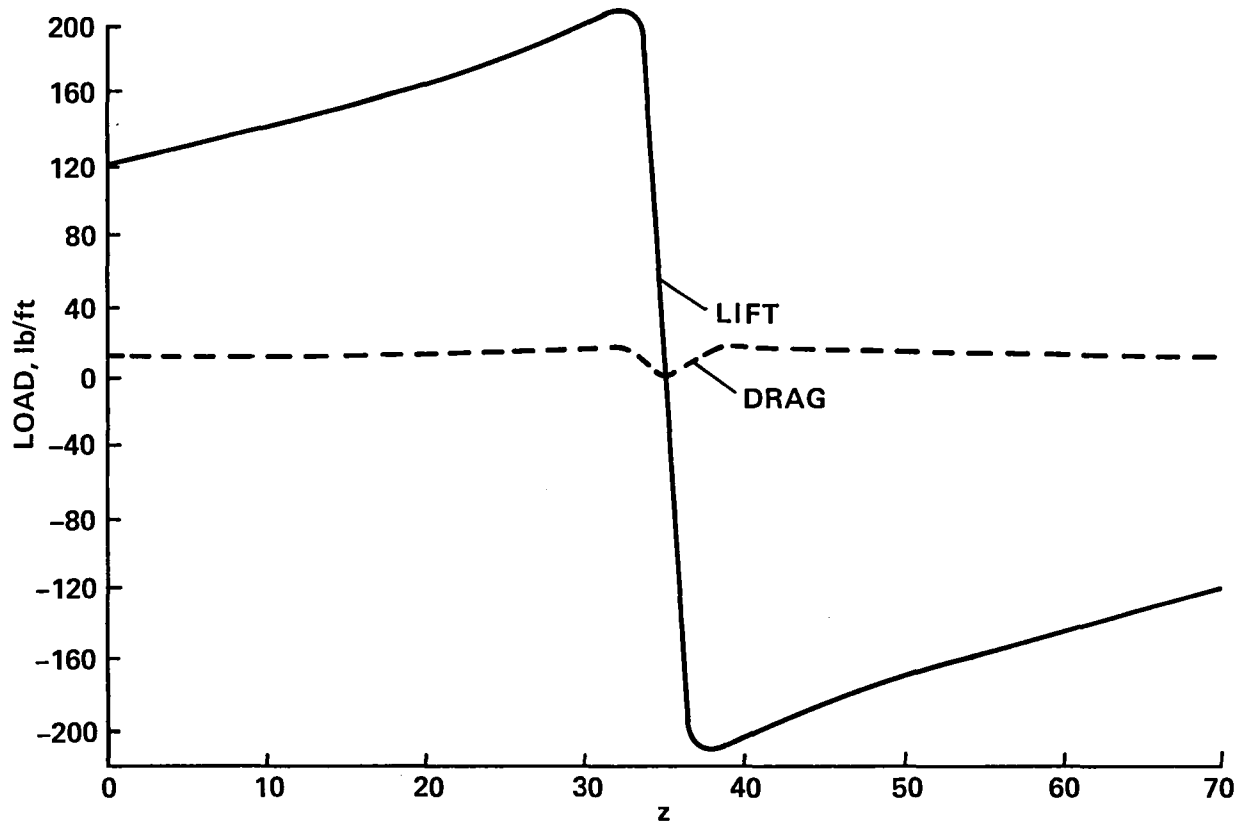


Figure 10.- Predicted vortex-induced load distribution on vane set 4. Vortex core at $z = 35$ ft.

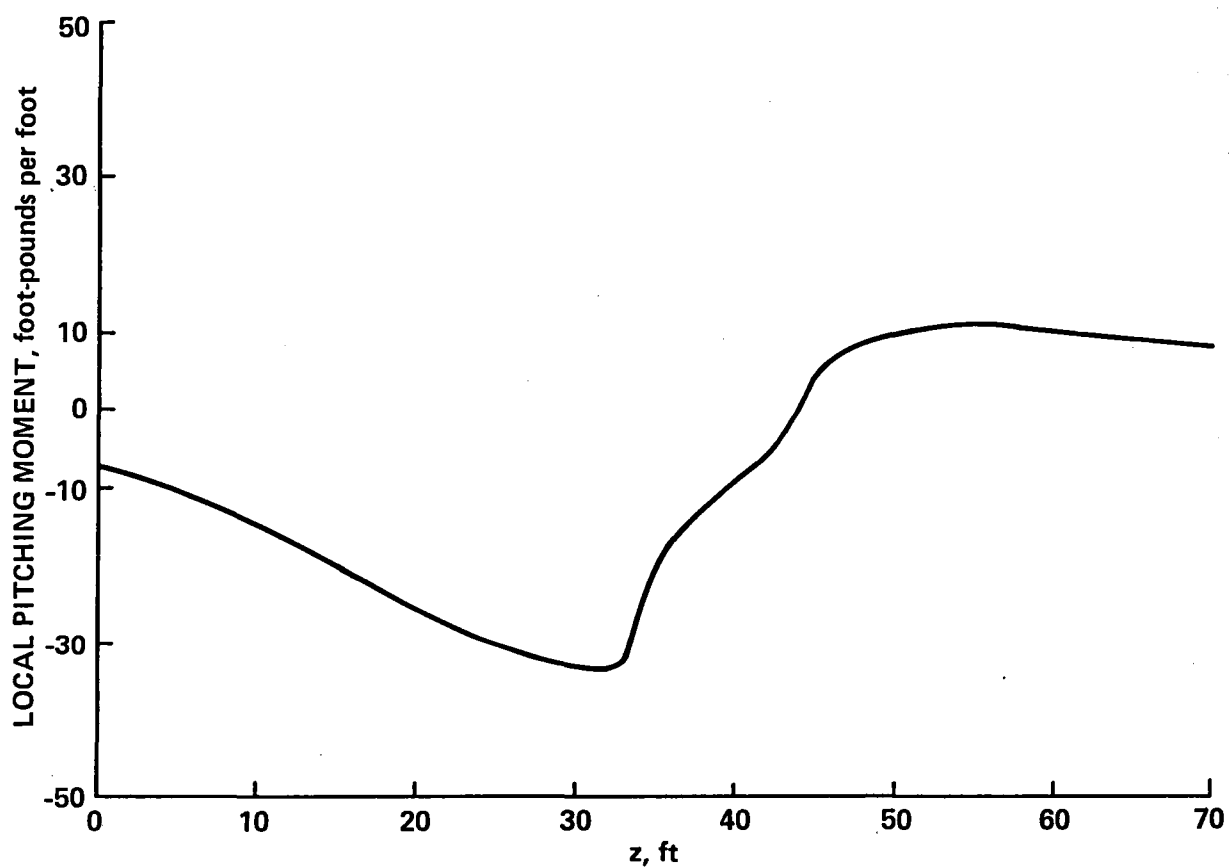


Figure 11.- Predicted vortex-induced pitching moment acting on vane 4. Vortex core at $z = 35$ ft.

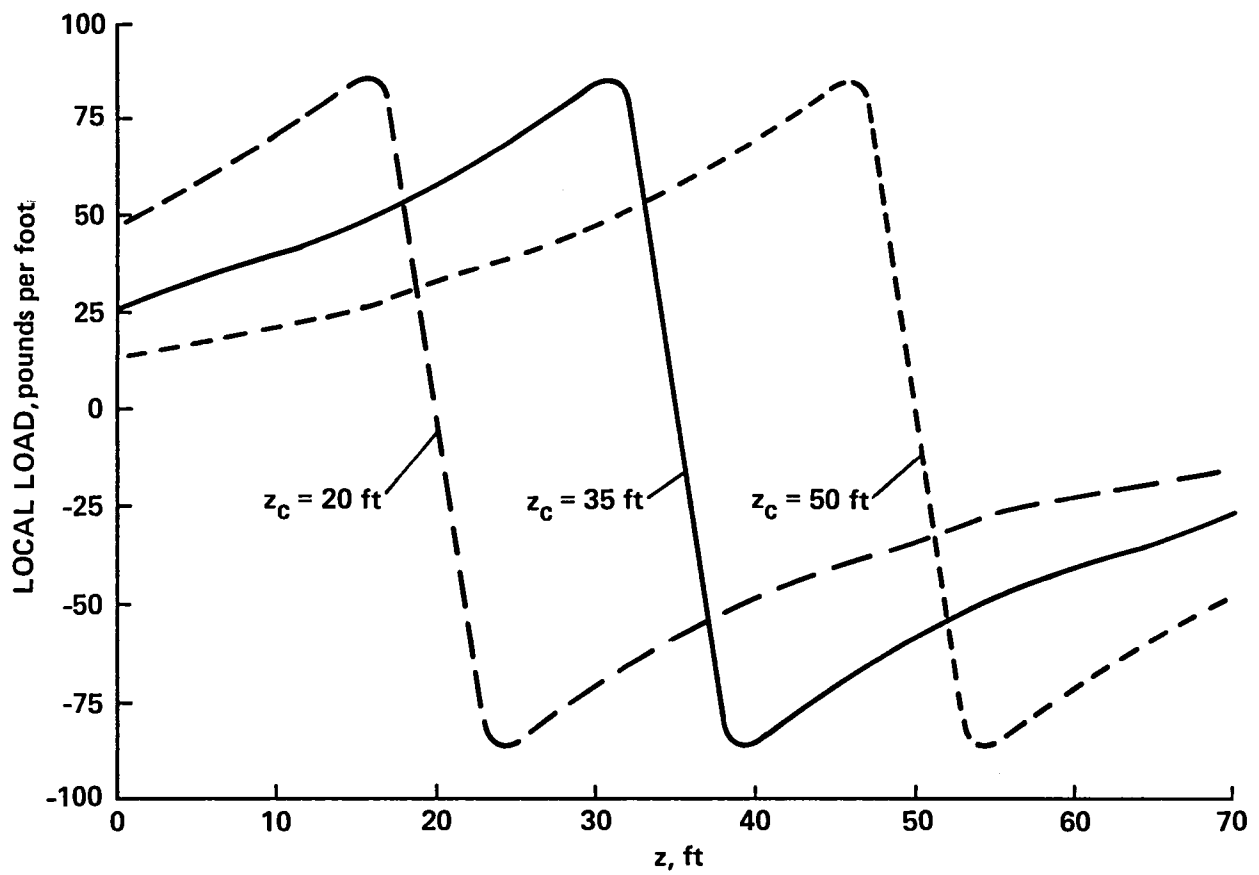


Figure 12.- Effect of vertical vortex displacement on predicted loading distribution of vane set 1.

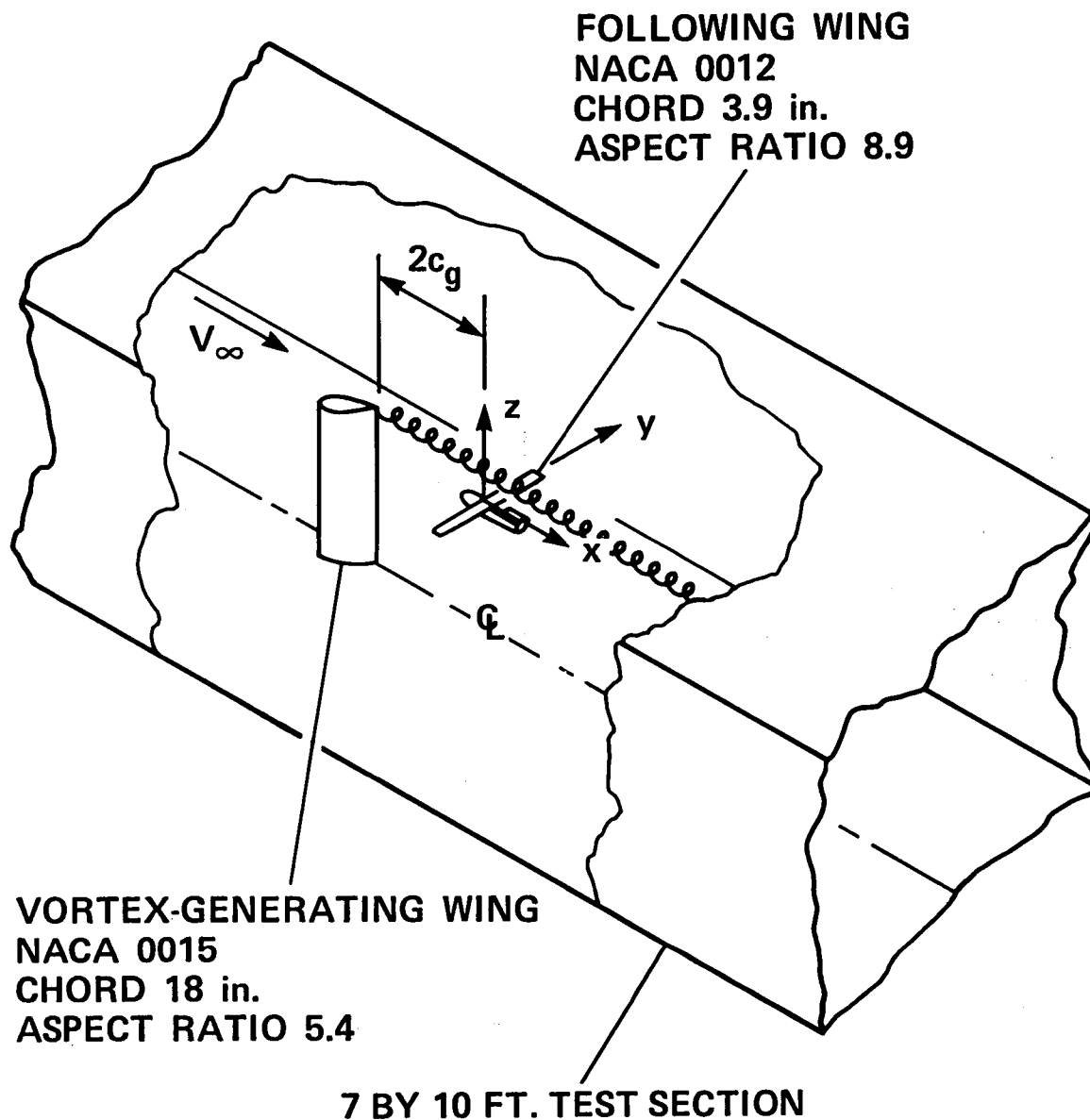


Figure 13.- Experimental arrangement of reference 3.

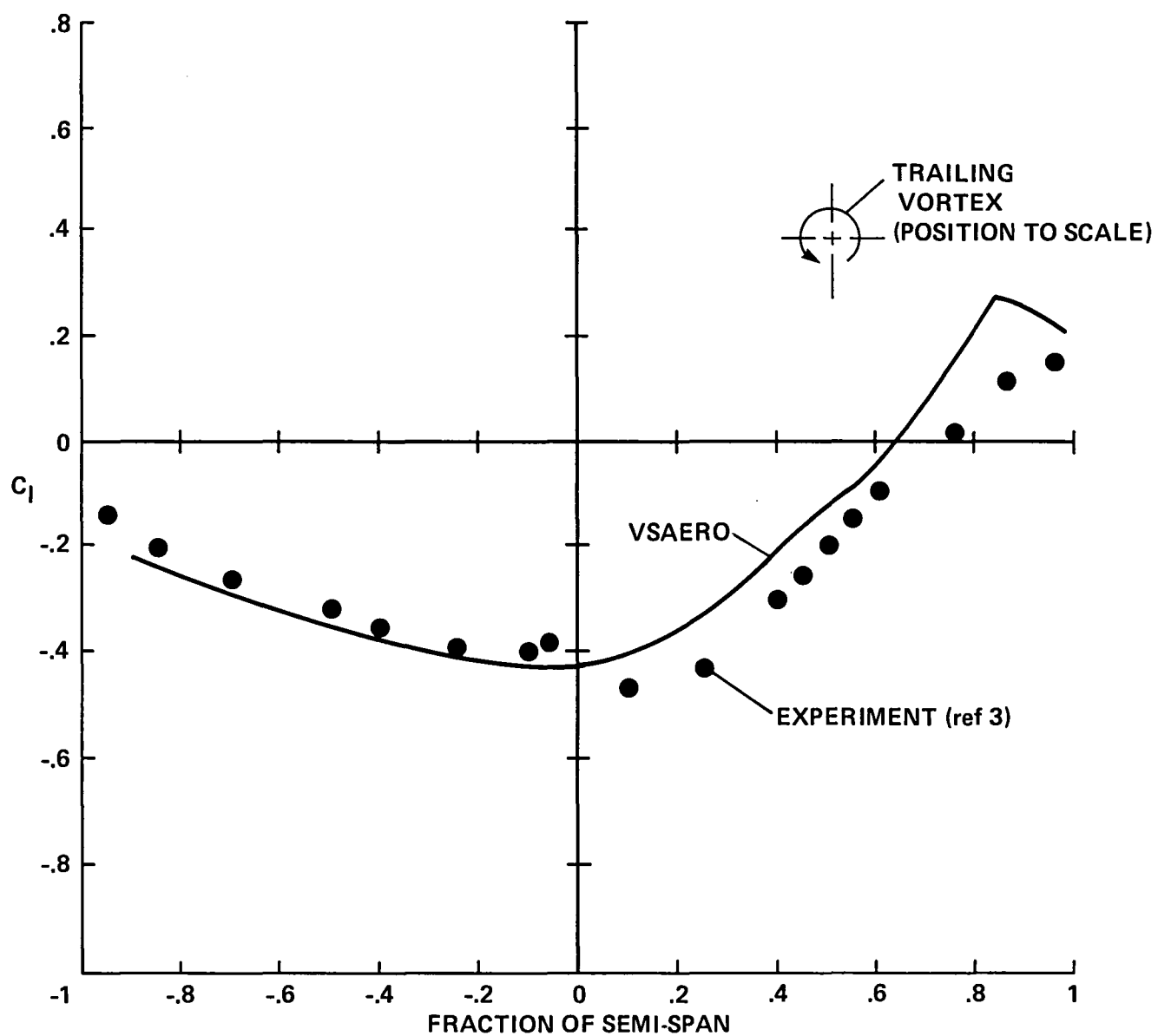


Figure 14.- Comparison of theoretical and experimental span loading from reference 3.

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